Alternate Configurations for Tethered Air Microclimate Cooling Systems

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Natick, Massachusetts

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6. AUTHOR(S)
Walter B. Teal, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Navy Clothing & Textile Research Facility
P. O. Box 59
Natick, MA 01760-0001

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At the request of the Naval Sea Systems Command, The Navy Clothing and Textile Research Facility conducted a laboratory evaluation of alternate hose configurations for use with air microclimate cooling systems (MCS). The configurations were evaluated for their effectiveness in improving user acceptance of the tether hose without adversely affecting cooling capacity or user performance. Four alternate configurations, plus a standard configuration were tested in benchtop and simulated shipboard tests.

The results of the benchtop tests indicated that the maximum flow rate difference between any two configurations was 1.0 standard cubic feet per minute at 90 psi feed pressure. This difference is not considered large enough to eliminate any particular configuration from further consideration.

The simulated shipboard tests indicated that there were no differences between configurations in terms of the time required to complete the course.

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ALTERNATE CONFIGURATIONS
FOR
TETHERED AIR MICROCLIMATE COOLING SYSTEMS

INTRODUCTION

In 1988 the Naval Sea Systems Command (NAVSEA) requested that the Navy Clothing and Textile Research Facility (NCTRF) conduct an investigation into and evaluation of alternate methods for managing the tether hose required by air microclimate cooling systems (MCS). NAVSEA is interested in providing microclimate cooling to certain shipboard personnel, but sailors have expressed concern over the management of tether hoses associated with air MCS.

Medical and performance problems resulting from work in hot environments have been well established. There are certain work spaces on board U.S. Navy ships, such as the engine room, and certain geographic locations, such as the Persian Gulf, which present particularly stressful environmental conditions to the sailor. To alleviate the problem of heat stress, microclimate cooling systems (MCS) have been developed. Studies have shown that MCS alleviate at least some of the medical and performance problems associated with heat stress under certain conditions (e.g., 1-4).

There are a variety of types of MCS, including passive ice, liquid, air, and refrigeration cycle MCS. One type currently used on board several Navy ships is the Steele Vest. This passive ice MCS consists of a vest with pockets into which frozen packets of a water-based gel are placed. Depending on the environmental conditions, the frozen packets provide cooling to the individual for up to two hours.

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(1) Pimental, N.A., and B.A. Avellini, Ph.D. Effectiveness of three portable cooling systems in reducing heat stress. Natick, MA: Navy Clothing and Textile Research Facility, 1987; Technical Report No. 176.

(2) Shapiro, Y., K.B. Pandolf, M.N. Sawka, M.M. Toner, F.R. Winsman, and R.F. Goldman. Auxiliary cooling: comparison of air cooled vs. water cooled vests in hot-dry and hot-wet environments. Aviation, Space and Environmental Medicine, 53:785-9, 1982

(3) Cosimini, H., J. Cohen, B. DeCristofano, R. Goff, V. Iacono, M. Kupcinskas, and T. Tassinari. Determination of the feasibility of two commercial portable microclimate cooling systems for military use. Natick, MA: US Army Natick Research and Development Center, 1985; Technical Report No. Natick/TR-85/033L.

(4) Pimental, N.A., B.A. Avellini, and C.R. Janik. Microclimate cooling systems: a physiological evaluation of two commercial systems. Natick, MA: Navy Clothing and Textile Research Facility, 1988; Technical Report No. 164.

Another type of MCS is the liquid circulating MCS. These systems, which are based on technology developed by NASA for cooling astronauts, consist of a backpack and a vest. An ice reserve is contained in the backpack, along with a pump and battery. A circulating fluid is pumped through the ice reserve and then through the fluid channels in the vest, thus cooling the individual, then returned to the ice reserve.

A variation of the liquid MCS is a dry ice version developed a few years ago at NCTRF (5). This device uses dry ice (solid carbon dioxide) instead of wet ice in the ice reserve of the backpack. In addition, the gas generated by the subliming dry ice is used to run the pump that circulates the fluid, thus eliminating the need for a battery.

A freon-based refrigeration cycle MCS has recently been developed on contract for the Air Force. The system uses a miniature vapor compression refrigeration cycle to cool the wearer. The vest itself is specially designed to function as the vaporization unit where freon expansion takes place to provide cooling. The compressor is run by a miniature diesel powered motor. Rigorous testing of this unit has not yet begun.

Air MCS consist of a vest, vortex tube, and compressed air source. Vests are made from an impermeable shell over a perforated or loosely woven lining. The shell prevents the air from escaping, while the liner distributes the air about the torso. A vortex tube is used to cool the compressed air before entering the vest. A vortex tube is approximately 1 inch in diameter and 10 inches long. Compressed air is supplied through an opening at approximately the mid-point of the tube. The internal construction of the tube generates a vortex which spins at speeds up to 1,000,000 rpm. It is theorized that at this high speed, centrifugal force separates fast moving molecules from slow moving molecules of air (6-8). The fast moving or hot molecules collect at the inner wall of the tube and are directed by the internal design of the tube out one end, while the slow moving or cold molecules collect in the center of the tube and are directed out the other end. In an air MCS, a hose is affixed to the cold end of the vortex tube and to the air distribution vest. Compressed air is supplied to the tube via a tether hose connected to a centralized compressed air source.

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(5) Audet, N.F., and G.M. Orner. Dry-ice, liquid-pulse-pump, portable cooling system. Natick, MA: Navy Clothing and Textile Research Facility, 1980; Technical Report No. 131.

(6) Janik, Carl. Air cooling laboratory test report. Natick, MA: Navy Clothing and Textile Research Facility, 1987; Internal report.

(7) Schiller, William A., and George M. Brown. The ranque-hilsch vortex tube. Fluid Mechanics in Chemical Engineering, Vol. 49:1013-6, 1957.

(8) Vortex Corporation, 1986, Brochure titled, Products for productivity.

Air MCS have several advantages over other types of MCS. Since the cooling is provided by the relatively small and lightweight vortex tube, air MCS are considerably lighter than other MCS designs, about 5 pounds versus 10 to 20 pounds. In addition, since there is no ice reserve or ice packs to melt, batteries to run down, or fuel supply to run out, air MCS are able to operate indefinitely without any additional logistic support, whereas other MCS require replacement or regeneration of the consumable items at regular intervals. The lack of these aforementioned items (ice, batteries, etc.) in an air MCS also makes the system less bulky by eliminating the need for a backpack, giving it a smaller profile, and thus making it easier for the user to maneuver through tight spaces. Finally, since air MCS allow the individual's sweat to evaporate readily, they tend to be more comfortable than other types of MCS which provide conductive, but not evaporative cooling. For these reasons, it is desirable to investigate the possibility of adapting air MCS for shipboard use.

There are, however, some disadvantages and unresolved problems associated with air MCS. The need for a centralized compressed air source creates some logistical problems. While compressed air is available in many work spaces on board Navy ships, the compressed air supplied is often dedicated for other purposes, especially on small and midsize vessels. Additional compressed air capacity would have to be installed on board most Navy ships before air MCS could be widely used. Before air MCS could be used in a Chemical Defense environment, some means of insuring clean air must be developed. The Army Natick Research, Development, and Engineering Center (NRDEC) is currently working on various types of filters which could be used. The current prototypes, however, are still too bulky for general use. In shipboard trials, sailors found the tether hose to be somewhat cumbersome; it frequently became tangled or caught on objects as the individual moved about (9). Because of the perceived lack of maneuverability with the air MCS, this system was not preferred by the sailors, despite its highly acceptable cooling power. NRDEC is developing a petroleum fuel-powered compressor that could be used in a backpack arrangement for supplying the compressed air. While this would eliminate the tether hose problem, it would increase the weight and bulk of the system, introduce the logistical problem of replenishing the fuel, and introduce a noise and fire hazard that would probably be unacceptable on board ship. An alternative to eliminating the tether hose is to make it more manageable by using a coiled hose, or by introducing swivel or elbow couplings. It is this alternative, finding ways to make the tether hose more manageable, which is the focus of this investigation.

The objective of this study was to modify the tether hose in some way so as to increase user acceptance, while not significantly affecting either the cooling capacity of the system, or the work performance of the user.

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(9) Janik, C.R., B.A. Avellini, and N.A. Pimental. Microclimate cooling systems: shipboard evaluation of commercial models. Natick, MA: Navy Clothing and Textile Research Facility, 1988; Technical Report No. 163.

METHODS

Configurations

Four alternative hose connection configurations, plus the standard hose were investigated. Three of the alternatives were additional connectors placed between the hose and quick disconnect coupling next to the vortex tube, and the fourth alternative consisted of various lengths of coiled hose used in place of the standard hose. When a tethered air MCS is used on board ship, it must be supplied with a breakaway fitting to permit rapid egress of personnel from compartments that may be flooding, burning, smoky, etc. During the field evaluation of air MCS, the fitting used was set at a breakaway force of 40 pounds (9). During the present study, the breakaway fittings were not used so that a test would not have to be aborted and repeated in the event of an unintentional breakaway.

a. Standard hose (STD). The standard hose is shown in Figure 1. It is 25 feet long and approximately 1 inch in diameter. It is connected to the air inlet of the vortex tube and to a compressed air source by means of a quick disconnect coupling. The standard configuration, including the quick disconnect couplings at each end, weighs slightly less than 5 pounds.

b. Straight connector with axial rotation (STRAIGHT). This connector, which is seen in Figure 2, is approximately 1-1/2 inches long by 1 inch diameter, and adds 2.6 ounces to the weight of the STD. It has external threads on one end and internal threads on the other. It is designed to allow one end to spin or rotate along the axis of the connector independently of the other end. This arrangement permits the hose to rotate to alleviate twists that develop in the hose during use. This configuration maintains the hose perpendicular to the axis of the vortex tube.

c. Elbow connector with hose side rotation (HOSE). Figure 3 depicts this connector, which is approximately 1-3/8 inches along one leg of the elbow and 1-3/4 inches along the other leg. The diameter of each leg is approximately 3/4 inch. The connector adds 2.8 ounces to the STD. Both legs of the connector have external threads. It is designed such that the longer leg is able to rotate on its axis. By connecting this leg to the hose, twists that develop in the hose during use may be alleviated. This arrangement is similar to the straight connector in that the rotation is along the axis of the hose, but it is different from the straight connector in that the hose is maintained parallel to the vortex tube.

d. Elbow connector with vortex tube side rotation (TUBE). This configuration, seen in Figure 4, utilizes the same elbow connector as the previous alternative. However, the longer (rotating) leg of the elbow is connected to the vortex tube rather than to the hose. While this does not provide the freedom of axial rotation for the hose as the previous two configurations, it does permit the hose to swivel in a plane parallel to the vortex tube.

e. Coiled hose (COIL25 and COIL50). In this configuration, shown in Figure 5, the standard air hose is replaced by a coiled air hose. Bench top tests were conducted on 25-foot and 50-foot lengths of coiled hose (COIL25 and COIL50, respectively), but only COIL50 was tested in the simulated shipboard evaluation for reasons described below. The coiled air hose is constructed of much lighter weight material than the standard air hose. The material used in the coiled hose is also much stiffer than that used in the standard hose, and it is doubtful that the hose would be very practical without the coiling effect built into the material during its manufacture. COIL50 weighs 2.2 pounds, and COIL25 weighs 1.5 pounds. Both of these measured weights include the weight of the quick disconnect coupling at each end. The coiled hose comes with a straight connector that permits axial rotation at one end (similar to the straight connector described above). This is required because of the axial rotation induced by stretching and then retracting the coil.

Bench Top Test

Bench top tests were conducted to determine the effect that each of the configurations under consideration would have on the flow of air to the vortex tube. The pressure of the air decreases as it flows from the compressed air source to the vortex tube. The total pressure decrease is called the pressure drop. Changing the path of the air flow by adding or removing connectors, changing the type or length of hose used, etc. will affect the pressure drop through the system. As the pressure drop changes, so does the air flow rate. At a particular supply pressure, the air flow rate will be less for a configuration with a higher pressure drop.

Pressure drop also affects the compressed air supply requirements. A configuration with a greater pressure drop will require a larger compressed air source to attain the same air flow rate. A pressure drop should not, by itself, cause one configuration to be selected over another. However, it is important to know how the configurations affect pressure drop and air flow rate so that engineers will be able to properly assess compressed air requirements when air MCS are being considered for installation on board ship. All other considerations being equal, a configuration which exhibits a lower pressure drop, and consequently, a higher flow rate and smaller compressed air requirements, would be preferred.

The test was designed to measure the pressure drop and flow rate of air of each configuration at a variety of supply pressures. Figure 6 is a diagram of the test set up. The pressurized air was provided by an air compressor manufactured by Ingersol-Rand. The maximum pressure that the compressor would generate was approximately 90 psi. The pressure of the air supply was controlled and monitored by a pressure regulator with a bourdon tube pressure gauge. A floating ball rotameter (flow meter) was used to measure the flow rate of air. The pressure of the air entering the configuration (feed pressure) to be tested was monitored by a bourdon tube pressure gauge. The pressure drop was measured by a differential mercury manometer. Quick disconnect couplings were attached to the two "T's" that lead to the manometer. This permitted easy connections for each of the configurations. A vortex tube was attached to the air outlet to provide some back pressure to the system. A breakaway fitting, which would be attached to the entrance of the vortex tube on board ship, was not used here, since its only effect would be to increase the back pressure slightly.

For each configuration, the pressure drop and flow rate was measured at several feed pressures. Once the configuration to be tested was connected to the system, the regulator valve was opened and adjusted so that the feed pressure was 45 psi. After the system came to equilibrium, the feed pressure, pressure drop, and flow rate were recorded. The test was repeated at feed pressures of 60, 75, and the maximum supply pressure available (approximately 90 psi).

In order to determine the repeatability of the test method, two preliminary test sequences were conducted. First, HOSE was tested five (5) times using different, but identical elbow connectors. The five results obtained were identical. This is not surprising, since the manufacture of metal parts such as these connectors is a very repeatable process. Second, STD, STRAIGHT, and HOSE were each tested independently by two operators. In each case, the operators obtained identical results. Since the results of these tests were highly reproducible, repeat tests were discontinued.

The flow rate versus feed pressure data were analyzed by linear regression, and then solved for the flow rate that would be obtained at 90 psi with each configuration. This pressure was chosen, since it is a typical feed pressure that could be made available (if not already available) on many ships. The flow rate obtained in this way was used to compare the configurations.

Simulated Shipboard Test

Simulated shipboard tests were conducted to determine which configuration would provide the best combination of user acceptance, shipboard mobility, and tether hose manageability. A previous study had identified the engine rooms, firerooms, scullery, and laundry as the shipboard spaces where most heat stress problems occur (9). The machinery space at Building 7 of NCTRF was selected as the best location for the simulated shipboard test. The machinery space contains various compressors, refrigeration units, heat exchangers, air handlers, duct work, and piping. It is similar to a shipboard engine room or fireroom in terms of the narrow passageways between pieces of machinery and the presence of piping which must be avoided during movements.

Typical engine room and fireroom tasks aboard ship consist of delivering messages, conducting repairs, reading gauges, recording the readings, and tweaking valves. These tasks generally require some mobility from place to place under somewhat cramped conditions. Occasionally, an alarm condition requires the individual to respond to a particular problem out of the normal routine of his work activities. These are the activities that were simulated in the simulated shipboard tests.

To standardize the movements of the subjects for test purposes, an obstacle course was set up in the machinery space. Figure 7 depicts a floor plan of the machinery space and obstacle course. The course required the subject to climb a ladder (about 6 feet), climb a set of stairs (about 10 steps), duck under a pipe (about 5 feet high), and step over floor level pipes in two locations. Several of the passageways were quite narrow, requiring the test subject to turn sideways. The complete course brought the subject back to the starting point of the course. A test consisted of five circuits through the course while wearing one of the hose configurations.

To simulate the common activities of reading gauges and tweaking valves, stacks of playing cards were placed at twelve locations along the course. The test subject, tethered with the hose configuration being tested, carried a clipboard and pen. At each stack of cards, the subject would turn over the top card and record its value. The routine circuit included ten stacks of cards. Five times during the test, a yellow alert alarm was sounded. Upon hearing the alarm, the subject would interrupt the routine activity, and respond to the alarm. Response to the alarm consisted of maneuvering to the eleventh stack of cards, recording the value of the top card on the stack, and then maneuvering back to the original location and resuming the routine circuit. Twice during each test, the yellow alert was interrupted by a red alert. When the alarm for the red alert was sounded, the subject would interrupt the yellow alert, respond to the red alert, and then resume responding to the yellow alert. The twelfth stack of cards was used for the red alert.

Five subjects, all of whom tested each of five hose configurations in random order, participated in the simulated shipboard test. During preliminary tests, it became apparent that COIL25 could not actually reach 25 feet, due to residual coiling which could not be easily removed by extending the hose. Since some parts of the planned test required the full 25-foot extension of the hose, COIL25 was dropped from the test. Each subject was tested on a different day. All five configurations were tested on the same day by each subject. Subjects executed several trial tests in order to become familiar with the test procedure before data collection began.

It was not necessary to strictly control parameters such as subject clothing and environmental conditions, nor was it necessary to provide compressed air to the vortex tube for cooling, since the objective of the test was to measure maneuverability (i.e. hose manageability, mobility, and acceptance), and not the cooling power of the MCS. Since the cooling effectiveness of air MCS has already been evaluated (e.g. 2, 6, 9), the tests were conducted at ambient conditions. The temperature was in the 70's or 80's degrees F. The ambient humidity was not measured. The test subjects wore clothing appropriate for the ambient conditions existing on the day of the test. Typically, this consisted of blue jeans or shorts, short sleeve shirt, athletic socks, and sneakers. The subjects did not wear the air distribution vest, due to the additional insulation it would have added, and because it was not required to distribute cooled air. The vortex tube was affixed to a web belt which was worn about the waist of the test subject. One end of the hose configuration being tested was affixed to the vortex tube. The other end of the hose was affixed to a stationary connector to represent connection to a compressed air supply system. The stationary connector was located approximately 8 feet above floor level. The hose was allowed to hang freely or drag across the floor, as required.

The test was monitored by someone familiar with the test procedure. A BASIC computer program was written to keep track of the time of the test, and to randomize the issuance of the yellow and red alerts. User acceptance was determined by asking subjects to rank the configurations in order of preference (1 = most preferred, 5 = least preferred). Mobility was measured by determining the time for each subject to complete five circuits (including the five yellow and two red alerts) with each configuration. Tether hose manageability was determined by counting the number of kinks that remained in the hose at the end of the test (kinks shorten the length of the hose), and by counting the number of hang-ups (defined as any catch of the hose on something which required the subject to retrace steps to become untangled) occurring during a test.

The simulated shipboard test data were statistically analyzed using one-way analysis of variance (configuration) for time to complete the obstacle course, total number of kinks and hang-ups, and subject preference. Tukey's test was used to locate the significant differences; significance was accepted at the 0.05 level.

RESULTS

Bench Top Test

The repeatable nature of these benchtop tests (as described earlier) implies that differences appearing in the results of the bench top tests are significant (statistically speaking). As expected, it is clear from Figure 8 that the pressure drop was dependent upon feed pressure. As the feed pressure increased, the pressure drop also increased. The pressure drop was also dependent upon the hose configuration, but to a lesser extent. The maximum difference between any two configurations at the same feed pressure is only about 5 psi.

The flow rate data, Figure 9, showed a similar variation among the configurations as the pressure drop data. The maximum difference between any two configurations at the same feed pressure is approximately 1 standard cubic feet per minute (SCFM).

Table 1 presents the flow rate of air at 90 psi for each configuration as determined by regression analysis. The maximum difference between flow rates is 1.0 SCFM. This difference is not considered large enough to eliminate any particular configuration from further consideration. COIL25 and STRAIGHT had flow rates very close to STD (within 0.1 SCFM), whereas COIL50, HOSE, and TUBE had somewhat lower flow rates than STD (0.6 to 0.9 SCFM less).

TABLE 1: FLOW RATE AT 90 PSI
(In order of decreasing flow rate.)

Configuration	Flow rate (SCFM)
COIL25	8.9
STD	8.8
STRAIGHT	8.7
COIL50	8.2
HOSE	8.1
TUBE	7.9

Simulated Shipboard Test

Time trial results are summarized in Table 2. The mean time for five subjects completing the test varied from 9 minutes, 30 seconds for STRAIGHT to 10 minutes 13 seconds for STD, a difference of only 43 seconds. There were no statistically significant differences between the time to complete the test for any of the configurations.

TABLE 2: TIME TRIAL RESULTS
(In order of increasing time.)
(Bracketed items are statistically indistinguishable.)

Configuration:	Time (Avg ± SD) (Minutes:Seconds)
STRAIGHT	9:30 ± 1:49
COIL50	9:37 ± 2:06
TUBE	9:38 ± 2:01
HOSE	9:59 ± 2:50
STD	10:13 ± 2:11

The HOSE, TUBE, and STRAIGHT configurations provided significantly fewer kinks and hang-ups than STD, as shown in Table 3. COIL50 was indistinguishable from any other configuration. It is worth noting that of the total of 4 kinks and hang-ups experienced by STRAIGHT, 3 of them occurred as hang-ups in one test.

Test subjects preferred HOSE over COIL50 as shown in Table 4. No other difference proved significant.

TABLE 3: KINKS AND HANG-UPS
(In order of increasing frequency.)
(Bracketed items are statistically indistinguishable.)

Configuration	Frequency (Avg ± SD) (Number per time trial.)
HOSE	0.0 ± 0.00
TUBE	0.2 ± 0.45
STRAIGHT	0.8 ± 1.30
COIL50	1.6 ± 1.34
STD	2.6 ± 0.89

TABLE 4: SUBJECT RANK
(In order of preference.)
(Bracketed items are statistically indistinguishable.)

Configuration	Rank (Avg $\pm$ SD)
HOSE	1.9 ± 1.02
STRAIGHT	2.2 ± 1.10
TUBE	2.7 ± 0.97
STD	3.8 ± 1.10
COIL50	4.4 ± 0.89

DISCUSSION AND CONCLUSIONS

Bench top tests indicated that, with the exception of COIL25, the use of alternate tether hose configurations (STRAIGHT, HOSE, TUBE, and COIL50) will result in greater pressure drop and decreased air flow rate for a given air supply pressure compared to STD. The increase in pressure drop and decrease in air flow rate resulting from the use of the alternate hose configurations is not considered sufficient to eliminate any configuration from further consideration. Ships considering the widespread use of air MCS must take the pressure drop and flow rate of the configuration being considered for use into account when determining the compressed air requirements. If the necessary compressor capacity is not available for the configuration being considered, then the ship's engineer (or other authority) must decide whether to add compressor capacity to accomodate the desired configuration, or switch to a different configuration that requires less compressor capacity. Ship's engineers trained in heating, ventilation, and air conditioning should be able to make the necessary calculations for their particular ship.

Based on the results of the simulated shipboard test, it is apparent that none of the alternate configurations will have either an adverse or beneficial affect on the time required for personnel to perform their duties. Some form of swivel connector (HOSE, TUBE, or STRAIGHT) will alleviate some of the hassle associated with tethered air microclimate cooling systems by reducing the frequency of kinks and hang-ups compared to STD. Test subjects preferred the HOSE configuration over COIL50, although other preferences were not as clear.

Any of the swivel connectors (STRAIGHT, HOSE, and TUBE) will improve air MCS tether hose manageability, due to their high user preference and minimization of hang-ups and kinks. If compressor capacity is a critical consideration, then the straight connector (STRAIGHT) is the configuration of choice. Coiled hose (COIL50) is not recommended for Navy personnel using air MCS.

Appendix A. Illustrations

FIGURE 1. STANDARD HOSE.

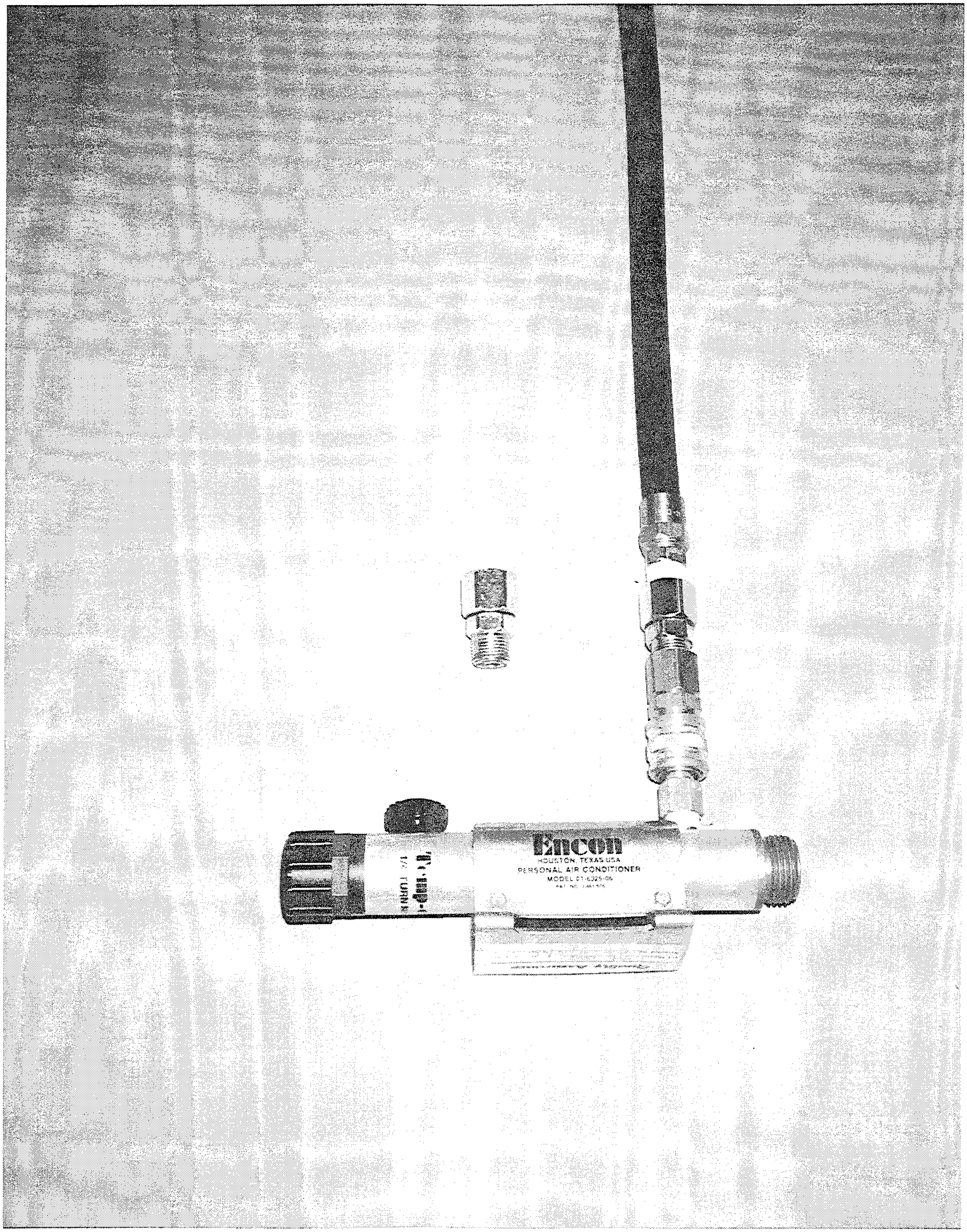

FIGURE 2. STRAIGHT CONNECTOR WITH AXIAL ROTATION.

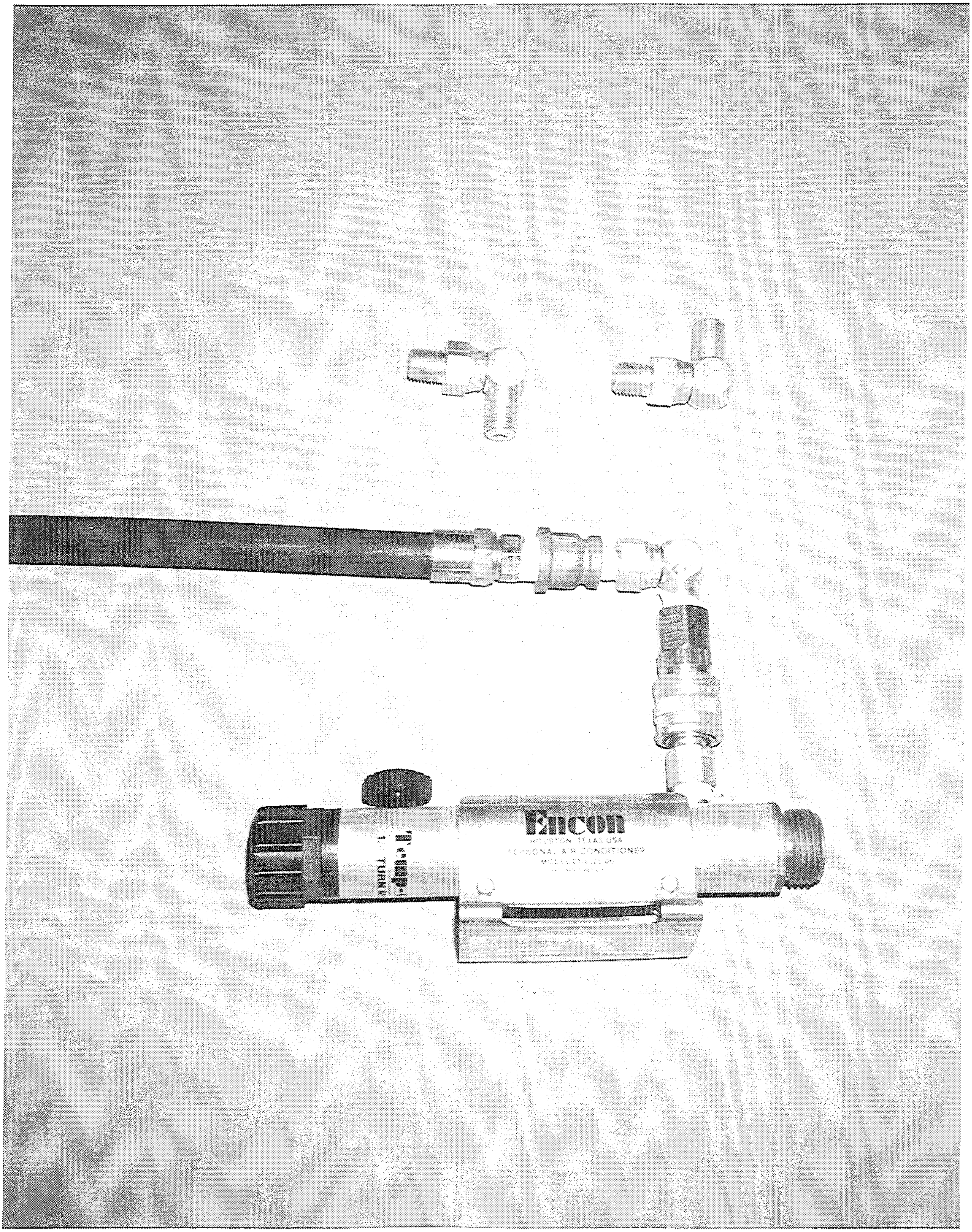

FIGURE 3. ELBOW CONNECTOR WITH HOSE SIDE ROTATION.

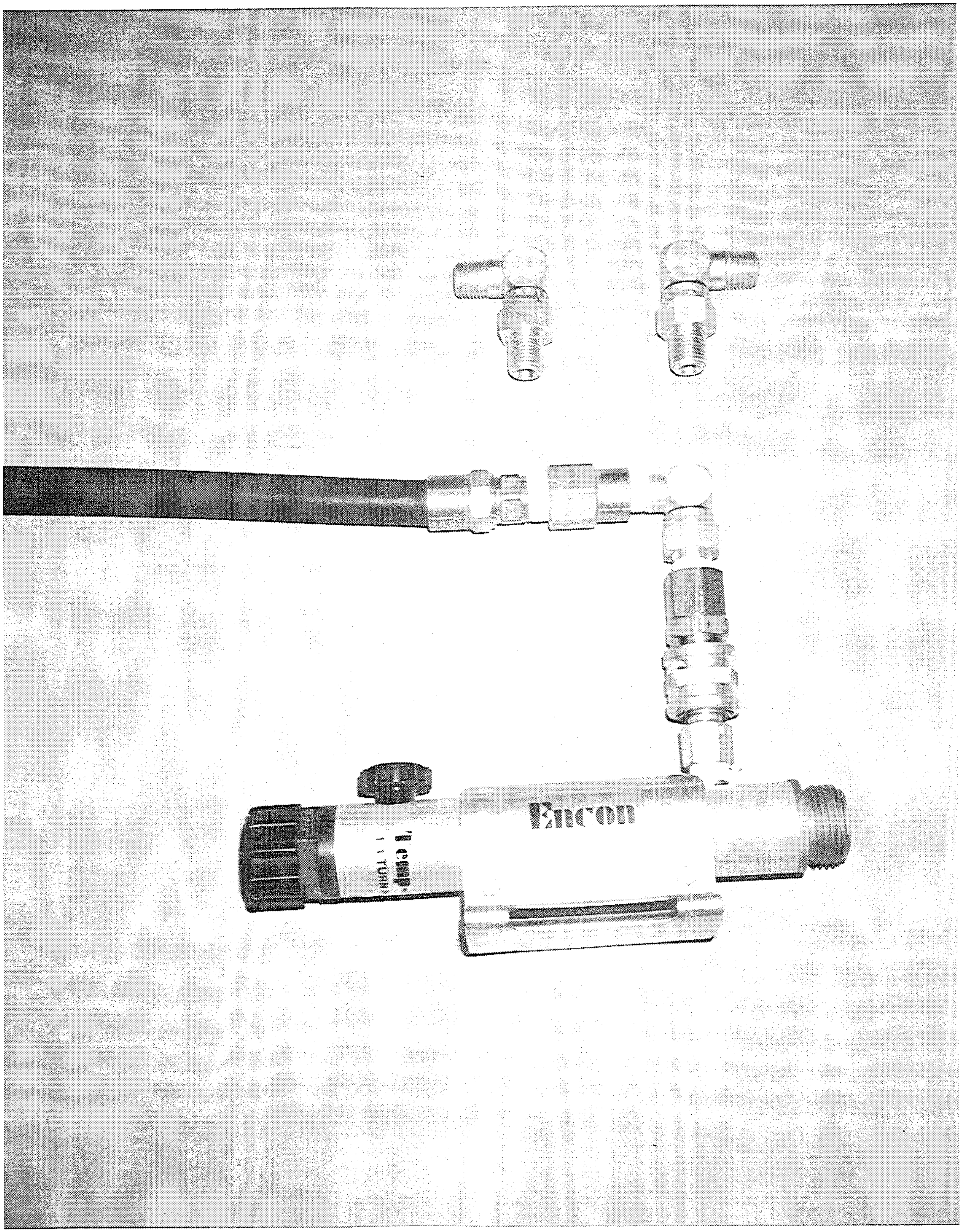

FIGURE 4. ELBOW CONNECTOR WITH TUBE SIDE ROTATION.

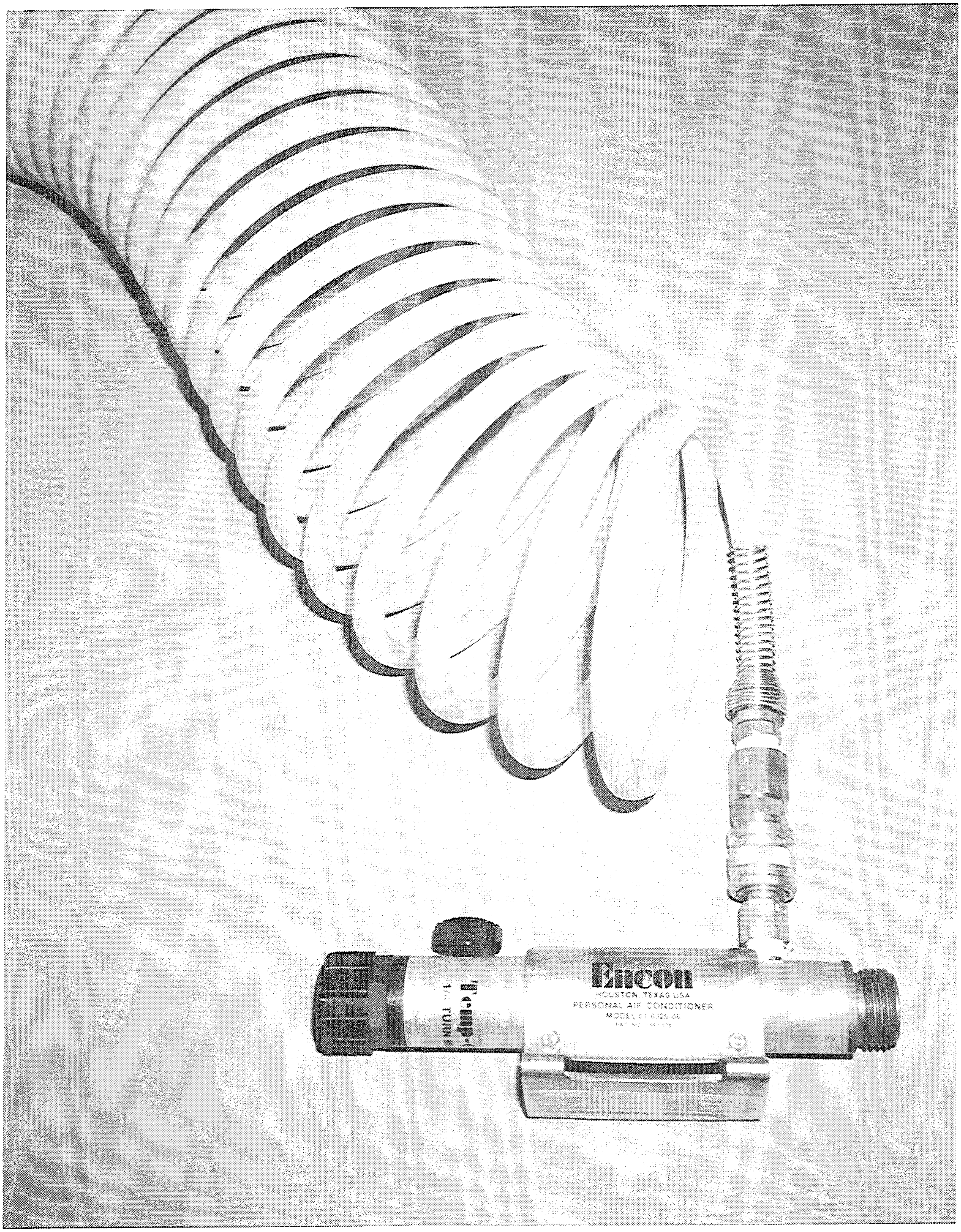

FIGURE 5. COILED HOSE.

Bench Top Test Setup

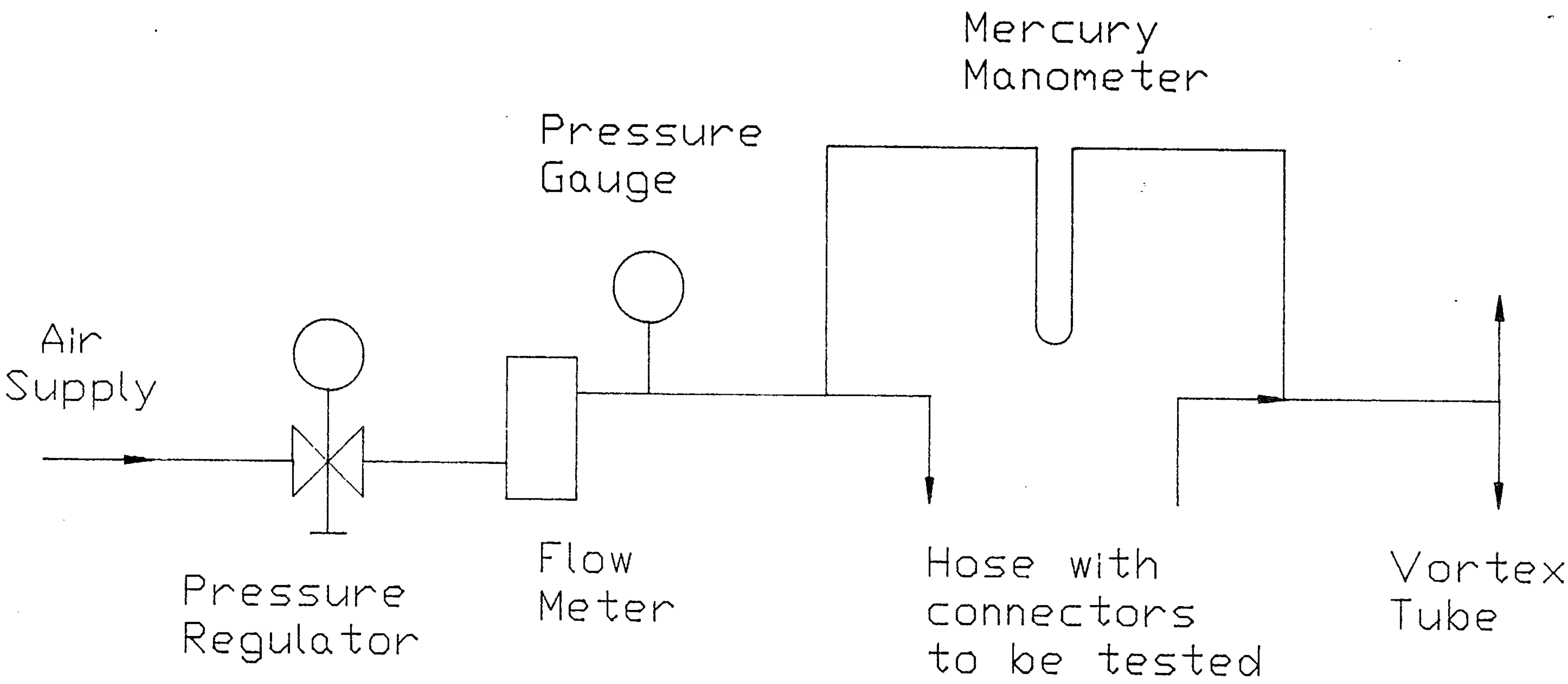

Figure 6

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AIR MICROCLIMATE COOLING
OBSTACLE COURSE ROOM 106
BUILDING #7 NCTRF

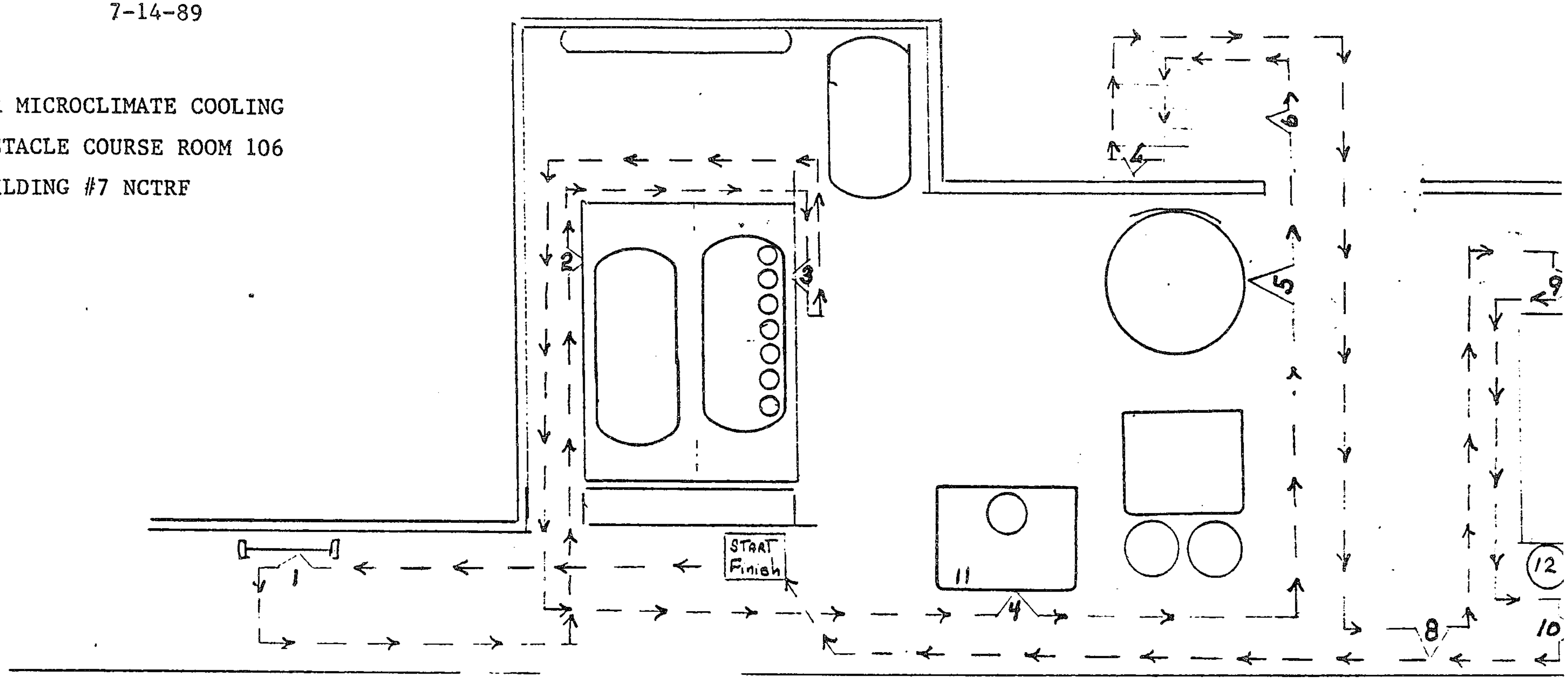

FIGURE 7. AIR MICROCLIMATE COOLING OBSTACLE COURSE.

PRESSURE DROP VS. FEED PRESSURE

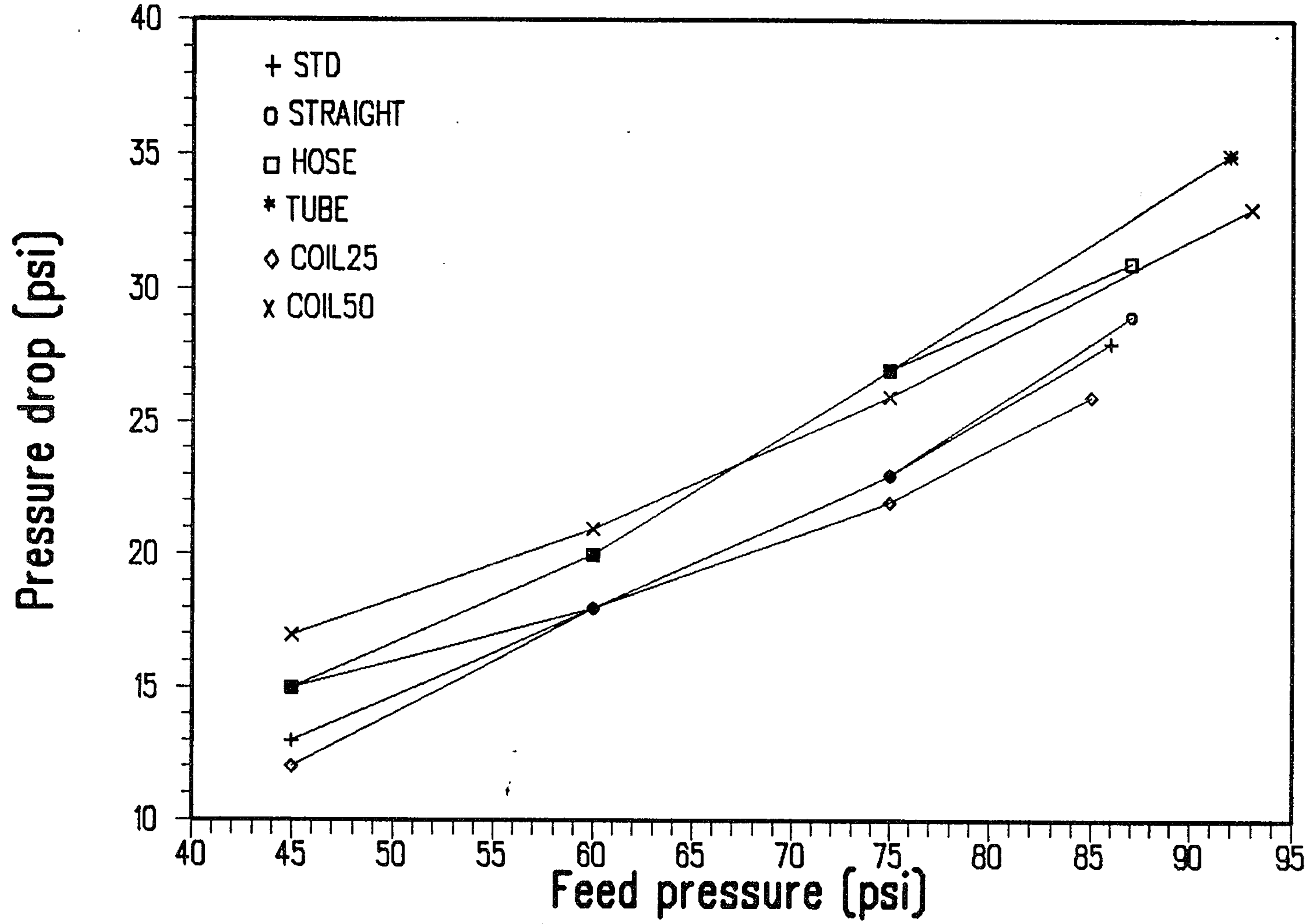

Figure 8. Pressure Drop vs. Feed Pressure

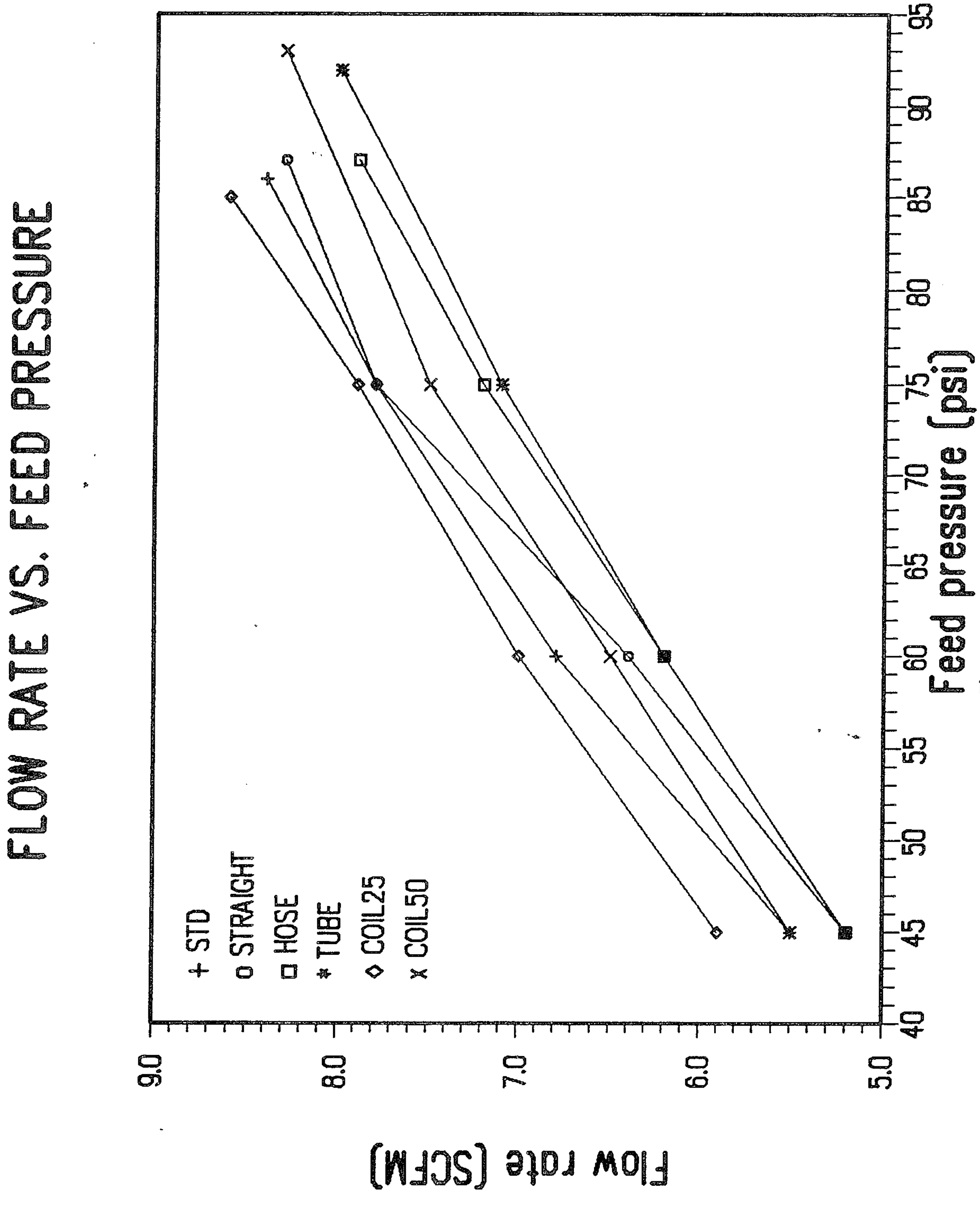

Figure 9. Flow Rate vs. Feed Pressure

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SCHOOL OF TEXTILE & FIBER ENGINEERING
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